SPS as LHC Injector I
Summary of Session 2

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1 INTRODUCTION

1.1 Aims of the session

The main aim of the session was to review the work done and progress made in the SPS during 2000 in preparing the proton beams for the LHC. The talks concentrated on work in the longitudinal plane.

Another aim was to take a first look at extraction from the SPS to the LHC.

1.2 Talks given in the session

Six talks were presented.

- Progress with LHC beams in the SPS seen from the Faraday Cage, T. Linnecar.
- Control of Strong Beam Loading. Results with Beam, Ph. Baudrenghien.
- How small are the SPS bunches at the moment?, T.Bohl.
- 400 MHz impedance, where are we?, E. Shaposhnikova.
- Controlling the beam for extraction: do we send it?, P. Collier.
- Are the physicists happy so far?, M. Bozzo.

1.3 Situation end 1999

The nominal beams for the LHC in the SPS, at extraction at 450 GeV, will consist of 3 or 4 batches spaced at 225 ns. Each batch will contain 72 bunches spaced at 25 ns. The nominal bunch parameters are:

- length τ_l = 2.5 ns,
- emittance ε_l = 0.7 to 1 eVs (the lower limit given by stability considerations in LHC and the upper by the capabilities or the LHC RF system),
- intensity N = 1.1 x 10^{11}.

This gives a maximum total SPS intensity of ~3.1 x 10^{13}.

During the shutdown, 1999/2000, the magnetic septa, MSE and MST had been shielded. In the next long shutdown, 2000/2001, the MKE kickers and 80 % of the pumping ports will be shielded and also all lepton equipment including the 3 accelerating systems will be removed. For the machine impedance reduction programme we were still far from the final situation.

At the end of 1999, beginning 2000, the maximum total intensity N accelerated to 450 GeV was:

1 batch	N = 4 x 10^{12},	5 x 10^{10} / bunch,
3 batches	N = 8 x 10^{12},	3.3 x 10^{10} / bunch.

2 PHYSICS

The proton physics run in 2000 started with the extraction of LHC type beams to the experimental areas for different LHC experiments to test prototype electronics chains in a realistic environment. For the machine this was an opportunity for a first test of stability of the acceleration systems and synchronisation errors etc. even though the test was at very low intensity 2 x 10^{12} in one batch. Three physics experiments ATLAS, CMS, LHCb used the beam and were happy with the quality of the beam (M. Bozzo). Results shown indicated that the jitter between arrival time of bunches and the reference signal was within tolerance, that the bunch length was correct and that there was no evidence of satellite (parasitic) bunches between the main bunches.

3 STUDIES ON THE LHC BEAM ACCELERATION CYCLE

The main aims of the MD programme in 2000 (SPS for LHC only) were:

- to see the effect on the beam of the introduction of hardware to combat severe beam-loading,
- to study instabilities and their effect on emittance blow-up along the cycle,
- to generally improve transmission along the cycle,
- to follow up the impedance reduction programme with reference measurements (started in 1999),
- to continue the identification of impedance sources responsible for instabilities.

3.1 Injection

The new triple splitting procedure was introduced during the year by the PS. 72 bunches can be produced per batch with this method rather than the ~80 using the old re-capture method. The bunch parameters are much more stable with intensity, typically τ_l = 4.3 ns and ε_l = 0.35 eVs, and in particular the bunch length at injection is now always below 5 ns, allowing better capture.

There is strong transient beam loading, the nominal beam induces 1.15 MV in each travelling wave (TW) cavity compared to the ~ 250 kV required for capture.

This is mainly due to the broadband impedance of the fundamental accelerating mode at 200 MHz. It leads to transient voltage changes along the batch and beam loss, a 1 MHz intensity modulation structure being created, and is fought by a combination of feedback and feed-forward around each cavity (Ph. Baudrenghien). This year the complete final solution was available for one cavity with feed-forward and reduced feedback on the other three.

Results shown for the complete solution applied to one cavity are very encouraging, a reduction in beam loading of better than 20 dB being obtained. The critical points are in the head and tail of the batch and are caused by fundamental limitations due to the transfer function characteristics of the cavities but also by imperfections in the power amplifiers. In particular a bandwidth limitation in the Siemens amplifiers and amplitude non-linearity in the Philips amplifier chain have been found. Some improvement in this area can be expected. The full solution, full bandwidth feedback and feed-forward around all cavities will be implemented in 2001.

3.2 Injection plateau

Continual improvements in the transverse plane reduced the losses along the injection plateau and reduction of the RF noise levels in the low-level electronics reduced longitudinal emittance blow-up. With this improved situation instabilities occur at random times during the ~ 11 s necessary for 4 batch injection (T. Linnecar). For multi-bunch operation the instabilities are predominantly a non-rigid dipole mode rather than the quadrupole mode observed with single bunches.

The instabilities could be suppressed using the 800 MHz Landau damping system at the intensities used, 8 x 10^{12} in 1 batch.

These instabilities were not studied in detail in 2000, since next year the machine should be significantly "cleaner".

3.3 Acceleration

The LHC beam is accelerated with 0.6 eVs bucket area (90 % filled) through the first part of the cycle. At high energies instabilities develop and emittance increases. Decreasing the voltage makes the situation worse even though the non-linearity of particle motion is increased, but the dependence on voltage is not strong. In fact the voltage must be increased at top energy to approach the required bunch length for transfer. The situation can be improved, until some moment in the cycle, by using Landau damping (T. Bohl). However there is always some blow-up when the total intensity is more than 4 x 10^{12}. The emittance at 450 GeV with 48 bunches, 8.3 x 10^{10} / bunch and Landau damping is 0.96 eVs, at the maximum of the allowed parameters. The Landau system however was not optimally adjusted in phase, a very critical parameter, and only one of the two cavities was available.

4 IMPEDANCE ISSUES

The aim of the impedance reduction programme is to cure and prevent single and multi-bunch instabilities. Studies in previous years had managed to identify many impedance sources in the SPS leading to the clean-up programme, now in full swing. Hardware details were mentioned earlier in the text.

Reference measurements were done from 1999 to quantify the impedance reduction achieved. These were to look at:

- global impedance effects - coherent frequency shifts and bunch lengthening. (A similar programme has been started for transverse impedance),
- impedances at particular frequencies - using methods developed over the last few years to look at instability thresholds, growth rates and mode amplitudes.

Beam measurements show a significant impedance around 400 MHz (mode amplitudes on single bunches with RF off, instabilities on single bunches at 26 GeV with RF on). A possible culprit was the combined effect of all the large tanks of the magnetic septa (MSE and MST). They were all shielded last shutdown. Comparison between mode amplitudes measured as a function of intensity at 200 MHz and 400 MHz in 1999 and 2000 showed initially some improvement (E. Shaposhnikova). However when these measurements are corrected for bunch length differences, which are shown by simulation to affect the result, the improvement is much smaller ~20%. Where does the impedance come from? Simulation shows that it cannot be simply the 2nd harmonic of the fundamental RF frequency, and recent bench measurements exclude the electrostatic septa (ZS), although these may have large impedance at other frequencies. Bench measurements indicate that a likely source is the kicker magnet modules and their tanks. Two out of the four will be shielded this shutdown. In 2003 we will have 11 kicker tanks so it is important to know now if they are the cause.

5 CONTROLLING THE BEAM FOR EXTRACTION

In other sessions during the workshop the risks of injecting out of tolerance beams were actively discussed from the LHC side. In this session two types of extraction vetoes in the SPS were identified and examples given (P. Collier):

- hardware oriented - involving equipment readiness from the SPS extraction elements, through the transfer lines to the LHC machine itself,
- beam quality vetoes - where tolerances must be defined, maybe on a cycle by cycle basis!

The latter can be further subdivided into:

• those generated by measurements on the beam currently in the machine,

• those generated by previous bad cycles.

In both cases a large amount of dynamic data should be acquired and digested just before extraction. Combined with the fact that the SPS has other users, such as CNGS, FT, safety, with other needs for the interlocks this makes for a very complex system. It seems that a complete re-think and re-design of the SPS interlock / veto system should be done and the man-power to do this made available.

6 CONCLUSIONS

The main conclusions for this session are as follows.

- The feed-forward/feedback upgrades give good results and are nearly complete. Improvements to the amplifier chains will be made.
- RF noise improvements were made reducing emittance increase on the flat bottom. This together with improvements in transmission (transverse plane) led to the observation of coupled-bunch instabilities of the non-rigid dipole type. These could be damped by the Landau cavities but detailed study is left until next year after the impedance reduction improvements.
- Longitudinal impedance reference measurements were followed up in preparation for the changes in the next long shutdown.
- A small reduction in the 400 MHz impedance has been obtained by shielding the MSE, MST tanks. The ZS separators do not make a significant contribution. The main source candidate at this frequency is now the kicker tank ensemble MKE, MKP. This must be closely followed (total of 11 tanks in 2003!).
- Instabilities at high energy are also a cause for concern. However improved operation of the Landau system and the reduction in impedance should give better results.
- Protection of the LHC from the SPS is complex and requires work to start now.
- Global progress with LHC beam in the SPS:

1999:

1 batch	4×10^{12} total	5×10^{10} / bunch
3 batches	8×10^{12} total	3.3×10^{10} / bunch.

2000:

1 batch	5×10^{12} total	6×10^{10} / bunch
3 batches	1.2×10^{13} total	5×10^{10} / bunch.

For 1 batch of 48 bunches, $N = 4 \times 10^{12}$ total, the longitudinal bunch emittance at 450 GeV is ~1 eVs. The transmission efficiency for this batch was 70%.

There has been good progress but there is still some way to go before we have the nominal LHC beams available in the SPS. Next year we will have a "cleaner machine" and so Chamonix XII should be very exciting!

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